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On the Significance of Population II ^{6}Li Abundances

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Abstract. We study the significance of ^{6}Li abundances measured in metal–poor halo stars. We explore possible depletion factors for ^{6}Li, defined as the ratio of the proto-stellar to the observed abundance, in the three stars where it has been detected; to this end, we assume that ^{6}Li/H scales as ^{16}O/H throughout the galactic evolution. This assumption is motivated by the recent observations of a similar scaling for ^{9}Be, and by the fact that, apart from $\alpha-\alpha$ fusion creation of ^{6}Li, both elements are only created in p,α–C,N,O spallation reactions. We examine possible uncertainties attached to the observations and to the modeling of ^{6}Li galactic evolution; notably, we include a recent evaluation of the primordial production of ^{6}Li. The depletion factor D_6 in the hottest turn-off star HD84937 is constrained to $D_6 \leq 4$; this implies that at least one star on the Spite plateau has not depleted its primordial ^{7}Li by more than a factor 4, even by extreme dilution. This constraint is in fact stronger when one takes all constraints into account; indeed, no current stellar model is able to reproduce the abundances of ^{7}Li as a function of metallicity and effective temperature, and yet allow $D_7 \geq 2$, while keeping $D_6 \leq 4$. Therefore, ^{7}Li should not be depleted by more than a factor $\simeq 2$ on the Spite plateau. If direct nuclear burning were the depletion mechanism, then ^{7}Li would be depleted by less than 2%. Moreover, all three ^{6}Li observations are in excellent agreement with all standard expectations: Big-Bang nucleosynthesis with $2 < \eta_{10} < 6.5$, and standard stellar isochrones of ^{6}Li survival in metal-poor stars. We also discuss possible deviations from our assumption of a scaling of ^{6}Li/H with ^{16}O/H, due to $\alpha-\alpha$ creation of ^{6}Li in various sites.

Subject Headings: *Cosmology: Nucleosynthesis – Stars: Abundances – Galaxy: Evolution*

1 Introduction

The light nuclide ^{6}Li is not significantly produced in standard Big–Bang nucleosynthesis, $(^6\text{Li/H})_p \sim 10^{-14}$ (Thomas et al., 1993; see below for a new evaluation), and is expected to be produced over the lifetime of the Galaxy in galactic cosmic rays (GCR) p,α–C,N,O spallation, as well as $\alpha - \alpha$ fusion reactions (Epstein, Arnett & Schramm, 1974; Reeves, 1994, for a review). Its high fragility to stellar processing makes it a powerful tool to constrain Big–Bang nucleosynthesis (Epstein, Arnett & Schramm, 1974), as was pointed out by Brown & Schramm (1988). It was argued that the survival fractions g_6, g_7, of ^{6}Li and ^{7}Li, defined as the ratios of the observed to the proto-stellar abundances (*i.e.* $\equiv 1/D$, where D is the depletion factor), should be related by $g_6 \approx g_7^\beta$, where $\beta \sim 60 - 76$ is the ratio of the destruction rate of ^{6}Li to that of ^{7}Li, in the case of nuclear destruction. Since $g_7 = 0.99$ already corresponds to a factor $\simeq 2$ destruction for ^{6}Li, and since the expected proto-stellar abundance of ^{6}Li in metal–poor stars is expected to be at the limit of feasible detection (see below), the detection of ^{6}Li in a metal–poor halo star could then be turned into a strong qualitative argument for the absence of significant (nuclear) depletion of ^{7}Li. In that case, the uniformity of the ^{7}Li abundances observed in metal–poor dwarfs on the so–called Spite plateau (Spite & Spite, 1982) should indeed reflect the primordial abundance of ^{7}Li. Such an abundance, $(^7\text{Li/H})_p \sim 1.6 \times 10^{-10}$, would be in excellent agreement with standard Big–Bang nucleosynthesis and the inferred primordial abundances of D and ^{4}He (Copi et al., 1995, and references therein). It should be noted that models where the surface abundances are depleted by mixing, and thus dilution with regions devoid of either ^{6}Li of ^{7}Li, are limited directly by the depletion factors.

It is extremely difficult to detect ^{6}Li in population II (PopII) stars, due to the weak isotopic separation of the ^{6}Li-^{7}Li λ6708Å lines, as compared to the width of the ^{7}Li line, and to the low expected isotopic ratio, $^6\text{Li}/^7\text{Li} \lesssim 0.1$, notwithstanding any possible destruction of ^{6}Li. A first detection was nonetheless reported by Smith et al. (1993) in HD84937, $^6\text{Li}/^{6+7}\text{Li}=0.05\pm0.02$. This result was confirmed independently by Hobbs & Thorburn (1994), who reported $^6\text{Li}/^7\text{Li}=0.07\pm0.03$ in the same star, as well as $^6\text{Li}/^7\text{Li}=0.05\pm0.02$ in HD201891; another marginal detection was reported in HD160617 by Nissen (1995), $^6\text{Li}/^{6+7}\text{Li}=0.017\pm0.012$.

Smith et al. (1993) were quick to point out the significance of their first measurement in HD84937. Using the observed abundances of boron and beryllium at low metallicities, and the $(\text{Li/B})_{GCR}$ production ratio expected from GCR spallation reactions in a PopII environment (Steigman & Walker, 1992), these authors showed that the isotopic ratio $^6\text{Li}/^7\text{Li}$ was in excellent agreement with: standard Big-Bang nucleosynthesis, *i.e.* $(^7\text{Li/H})_p \sim 10^{-10}$, no depletion of ^{7}Li, possibly little destruction of ^{6}Li, and no significant primordial production of ^{6}Li. Moreover, these authors showed that in the case of rotational stellar models, which predict large destruction factors for ^{7}Li, $g_7 \sim 0.1$, and for ^{6}Li, $g_6 \lesssim 0.04$, the measured isotopic ratio in HD84937 implies either one of the following: *(i)* a massive production of lithium isotopes in $\alpha - \alpha$ fusion reactions in a very

early phase of the Galaxy; *(ii)* a very high primordial abundance of ^{6}Li and ^{7}Li, in a non-standard Big-Bang nucleosynthesis scenario; or *(iii) in-situ* synthesis of ^{6}Li in HD84937, for instance in stellar flares. We examine these different cases in Sec.3. Steigman et al. (1993) reached very similar conclusions using the observed ^{9}Be abundance in HD84937: they found agreement with standard Big-Bang nucleosynthesis, with no depletion of ^{7}Li and ^{9}Be, and possibly moderate depletion of ^{6}Li, $g_6 \gtrsim 0.2$, as predicted by non-rotating standard stellar models. They also argued that these ^{6}Li observations posed a severe challenge to the so-called Yale rotational stellar models.

A potential problem with these two approaches is that they rely entirely on the knowledge of the $(\mathrm{Li/Be})_{GCR}$ production ratio at low metallicities, and it is now accepted that this ratio is in fact very uncertain (Fields et al., 1994, 1995). Indeed, the naive extrapolation at low metallicities of standard galactic cosmic ray (GCR) spallation is in apparent conflict with the observed abundances of ^{9}Be and B in PopII stars, since it predicts a slope $\simeq$2 for the correlations of Log(Be/H) and Log(B/H) *vs* [Fe/H], whereas a slope $\simeq 1 \pm 0.1$ is observed (*e.g.* Rebolo et al., 1988, Gilmore et al., 1992a, b, Ryan et al., 1992, Boesgaard & King, 1993, and references, for Be; Duncan et al., 1996a, b and references, for B). In order to explain these primary behaviors of ^{9}Be and B, different scenarios have been suggested: some involve modifying the GCR scenario (Duncan et al., 1992; Prantzos et al., 1993; Feltzing & Gustafsson, 1994), some others modify the chemical evolution in the halo phase (Ryan et al., 1992; Fields et al., 1993, Tayler, 1995), while some others invoke different spallation processes (Cassé et al., 1995; Vangioni-Flam et al., 1995). Moreover, whereas Steigman & Walker (1992) have shown that the $(\mathrm{Li/Be})_{GCR}$ production ratio depends in a crucial way on the metallicity of the medium, Fields et al. (1994, 1995) have shown that it also depends quite strongly on the physical parameters of the GCR flux (*e.g.* spectral exponent and path length). Overall, it appears that this production ratio can be very different in the above models of early ^{9}Be and B evolution, taking values in the range $\sim 10 - 1000$.

In the present paper, we offer a simple prescription that allows us to circumvent the model dependent uncertainties, hence to derive empirical proto-stellar ^{6}Li abundances. We simply assume that ^{6}Li scales as oxygen at all metallicities. Such a behavior is indeed observed for ^{9}Be, and any (p,α–C,N,O) spallation process which creates ^{9}Be should also produce ^{6}Li, in the same way, and vice-versa (see also below). We justify this prescription further in Sec.2. We then construct a predicted evolutionary curve for ^{6}Li, and normalize it to the ^{6}Li meteoritic abundance. It is then straightforward to obtain the possible depletion factors for ^{6}Li in HD84937, HD201891, and HD160617 (Sec.2). We also discuss alternatives to this model (Sec.3): these can only arise from $\alpha - \alpha$ fusion, since this is the only channel whereby ^{6}Li and not ^{9}Be can be produced.

2 Standard expectations

2.1 Early ^{6}Li evolution

The yield of ^{9}Be in a generic spallation process of flux ϕ may be written:

$$\frac{dy_{\rm Be}}{dt} \approx \langle \phi_i \sigma_{iZ}^{\rm Be} y_Z \rangle + \langle \phi_Z \sigma_{Zi}^{\rm Be} y_i \rangle, \tag{1}$$

where i runs over p, α, and Z runs over C,N,O; y denotes the abundance with respect to hydrogen; the average is performed over energy and source and target composition; stopping factors due to energy losses and/or escape are implicitly included as form factors on the cross-sections. As has been extensively discussed in the literature (Vangioni-Flam et al., 1990; Fields et al., 1994), the standard GCR yields are proportional to the time derivative of the oxygen abundance squared y_O^2, giving rise to the slope 2, because the GCR flux ϕ_i is proportional to the supernova rate, the y_Z abundances are proportional to the integrated supernova rate, and the flux ϕ_Z is proportional to the product of these two factors. As discussed in Fields et al. (1994) and Lemoine et al. (1996), one can escape this slope 2 in at least three ways: *(i)* by adjusting the Z dependence of the flux ϕ_i (Fields et al., 1993); *(ii)* by keeping y_Z constant (Gilmore et al., 1992b; Feltzing & Gustafsson, 1994; Tayler, 1995); and *(iii)* by adjusting the ϕ_Z dependence on the supernova rate (Duncan et al., 1992; Vangioni-Flam et al., 1995; Cassé et al., 1995). The inclusion of Tayler (1995) in category *(ii)* is not obvious, due to the peculiarity of this model; it is discussed in Sec.3. Note that Feltzing & Gustafsson (1994) have shown that spallation in the vicinity of supernovae, as advocated by Gilmore et al. (1992b), is probably not energetically viable, hence we will refer to such models only as an example of category *(ii)* above. As well, we note that Lambert (1995) proposed to explain the halo abundances of ^{6}Li, Be and B by direct production of these elements in the observed stars from cosmic rays impinging on the stellar atmospheres. He showed that this scenario was not viable for Be and B, and barely able to reproduce the ^{6}Li abundances.

It is then straightforward to derive the scaling of ^{6}Li with metallicity, rewriting Eq.(1) for ^{6}Li:

$$\frac{dy_{\rm Li}}{dt} \approx \langle \phi_\alpha \sigma_{\alpha\alpha}^{\rm Li} y_\alpha \rangle + \langle \phi_i \sigma_{iZ}^{\rm Li} y_Z \rangle + \langle \phi_Z \sigma_{Zi}^{\rm Li} y_i \rangle. \tag{2}$$

In cases *(ii)* and *(iii)*, the yields of ^{6}Li scale as the supernova rate. Only in the first scenario does the behavior of ^{6}Li deviate from that of a primary element. Indeed, appropriately adjusting the flux can make the ^{9}Be correlation go from quadratic to linear, in which case the ^{6}Li correlation goes from linear to ∼constant through the $\alpha - \alpha$ fusion channel. This is easily seen by parametrizing the metallicity as a power-law in time, $y_{Fe} \propto t^n$ (note that y_{Fe} is the iron abundance <u>not</u> in logarithmic units); tuning the flux so as to obtain a slope 1 for Be and B then leads to: $\log(^6{\rm Li/H}) \propto \log\left({\rm constant} + [{\rm Fe/H}]\right)$. However, as we discuss in Sec.3, it is not obvious why and how such a tuning of the flux could take place in the halo phase.

This brief discussion shows that, under very general conditions, ^{6}Li should behave as a primary element in the halo phase. However, our prescription further requires that this

scaling holds equally well up to solar metallicities, *i.e.* that the transition from the halo to the disk phase proceeds without any change in the (^{6}Li/O) production ratio. Here, we distinguish two different cases: *(i)* where GCR are responsible for the halo evolution of LiBeB, through some modification of their parameters or some modifications of the galactic evolution; and *(ii)* where another process than GCR accounts for the evolution of LiBeB in the halo phase. In the first case *(i)*, we note that, for GCR spallation and fusion, at a given (low) metallicity, although (^{6}Li/O) depends more strongly than (^{9}Be/O) on the very low energy part ~ 10 MeV/n of the GCR spectrum, due to the low energy $\alpha-\alpha$ cross sections, it depends less strongly on the spectral slope and the path length, that affect the higher energy part of the spectrum. We note as well, that, within observational accuracy, the (^{9}Be/O) ratio keeps constant from the halo to the disk phase (see Fig.2). It is therefore reasonable to assume that, in case *(i)*, the (^{6}Li/O) production ratio has not changed significantly between the halo and the disk phase. In the second case *(ii)*, we can reasonably assume that the process responsible for the evolution of Be and B in the halo phase, proceeds on into the disk phase, and that the production ratio (^{6}Li/O) ratio does not change. This is indeed what Fig.2 suggests. One knows as well that standard GCR spallation/fusion creates ^{6}Li as a primary element in both halo and disk phase. When mixing these two processes of creation of ^{6}Li, one mixes two primary processes, and one obtains a primary process. In this case, therefore, there is no change of slope or of production ratio (^{6}Li/O).

Finally, the constancy of the ratio (^{6}Li/O) ratio is shown to hold for the models referred to in *(ii)* and *(iii)*, except Tayler (1995); in this latter scenario, the (^{9}Be/O) ratio in the halo phase is arbitrarily tuned to that in the disk phase, but it is not possible to make definite predictions for the (Li/O) ratio. We discuss this model further in Sec.3. In any case, we allow, in assigning error bars for our predicted evolutionary curve, for some possible (slight) mismatch in the (^{6}Li/O) production ratio between the halo and the disk phase.

2.2 ^{6}Li as a primary element

In order to construct the evolutionary curve of ^{6}Li, we use a simple model of chemical evolution. This model is a closed box, one zone model based on the Tinsley (1980) formalism, able to reproduce the trends in C, N, O, [C/Fe]$\sim$[N/Fe]≈ 0, [O/Fe]≈ 0.5 in the halo phase (Wheeler et al., 1989), together with the age-metallicity relation, and the solar abundances of C, N, O, and Fe at solar metallicity. This model incorporates a GCR code for production of LiBeB. We used this model in order to take into account the slope changing effect on the ^{6}Li–Fe relation in the disk phase, due to the introduction of Type Ia supernovae, *i.e.* in order to follow [O/Fe]. It is sufficient for our purpose to use the standard GCR calculations of spallation/fusion production of ^{6}Li, with a flux proportional to the supernova rate, as these calculations yield the desired primary behavior. More complex issues of galactic evolution, such as supernovae ejecting metals to form a hot

intergalactic gas (Mathews & Schramm, 1993) are irrelevant here.

We note that the upper limit on the primordial abundance of ^{6}Li has recently been revised upwards by two orders of magnitude, through new measurements and limits on the cross-section d(α,γ)^{6}Li at low energies (Cecil et al., 1996). We included this upper limit in the predicted curve, *viz.* $(^6\mathrm{Li/H})_p \leq 1.2 \times 10^{-12}$, although it has no effect on our calculations, since the metallicities where ^{6}Li has been detected are too "high" for this primordial component to be relevant. Nonetheless, as we show in Fig.1, this could be of relevance for metallicities [Fe/H]$\lesssim -3$, depending of course on the actual primordial abundance of ^{6}Li. This will be discussed in detail in Nollett et al. (1997).

We thus construct the ^{6}Li evolutionary curve, and normalize it to the meteoritic abundance of ^{6}Li, as shown in Fig.1. Data points for ^{6}Li were taken from Smith et al. (1993), Hobbs & Thorburn (1994), Nissen (1995), and Nissen et al. (1995), and are reproduced in Table 1. We did not consider in these data upper limits that were previously obtained by Andersen et al. (1984), Maurice et al. (1984), Hobbs (1985), and Pilachowski et al. (1989); although these observations certainly represented a challenge at that time, the upper limits obtained, $^6\mathrm{Li}/^7\mathrm{Li} < 0.1$ in all cases, are unfortunately not stringent enough for our purpose. Data points for ^{7}Li and ^{9}Be come from a compilation of Spite & Spite (1982), Boesgaard & Tripicco (1986), Hobbs & Duncan (1987), Rebolo et al. (1988), Pilachowski et al. (1993), Gilmore et al. (1992a, 1992b), Ryan et al. (1992), Boesgaard & King (1993), Smith et al. (1993), Hobbs & Thorburn (1994), Thorburn (1994), Duncan et al. (1996a, b), Molaro et al. (1995), Nissen et al. (1995), Rebolo et al. (1995), Spite et al. (1996), and Anders & Grevesse (1989).

The ^{7}Li abundances, [Fe/H], and T_{eff} for the ^{6}Li stars were taken from Smith et al. (1993), Hobbs & Thorburn (1994), Thorburn (1994), Nissen (1995), Nissen et al. (1995), Primas (1995), Spite et al. (1996), and Ryan et al. (1996); see Table 1. We adopted, as error on the temperatures, 150K statistical, and 100K systematic, at 95% c.l., following Spite et al. (1996). Note that, contrary to elemental abundances, the isotopic ratio is only weakly sensitive to the [Fe/H] and T_{eff} adopted; for instance, the ^{7}Li abundance of HD84937 as derived by Thorburn (1994) is 0.24dex higher than that derived by Smith et al. (1993), although the isotopic ratios are entirely consistent. For this star, both $^6\mathrm{Li}/^{6+7}\mathrm{Li}$ evaluations were combined in a weighted least squares procedure.

We adopted a ± 0.16dex 2σ statistical gaussian uncertainty for lithium and iron abundances, which is a typical estimate (Thorburn, 1994; Spite et al., 1996). We adopted a ± 0.2dex 95% c.l. systematic uncertainty for lithium and iron abundances, a typical estimate as well (Thorburn, 1994; Spite, 1995; Spite et al., 1996). In Fig.1, we combined these systematics on the ^{7}Li and ^{6}Li abundances quadratically with the 2σ statistical error bars, in order to produce an estimate of the total 95% c.l. on these data points. In the following analysis, however, we allow for different statistics. Namely, we take the abundance systematics on N[Li] and [Fe/H] to follow top–hat probablity laws, and the $^6\mathrm{Li}/^{6+7}\mathrm{Li}$ ratios to follow gaussian laws. We adopted a ± 0.3dex 95% c.l. uncertainty on our evolutionary curve, which we can attribute to the normalization to the meteoritic abundance of ^{6}Li

as well as to slope changing effects of chemical evolution at the halo-disk transition. Indeed, although the meteoritic abundance of ^{6}Li, as given by Anders & Grevesse (1989), is endowed with very small error bars, ± 0.04dex, we prefer to remain conservative and allow for a possible 2σ uncertainty $\simeq \pm 0.2$dex in promoting this meteoritic abundance to a 'cosmic' abundance at [Fe/H]=0. We show, in Fig.2, how well this evolutionary curve, and its accompanying error bars, bracket the Be observations in halo stars. We always refer to ^{9}Be as a baseline, and not to B, since the available boron abundances have not yet been fully corrected for NLTE effects. Let us mention, however, that a clear primary correlation for boron *vs* iron in the halo phase, with a slope $\simeq 1.0 \pm 0.05$, is inferred from these latter abundances (Duncan et al., 1996a,b).

We now discuss the three detections of ^{6}Li in HD84937, HD201891, and HD160617. The upper limits located above the evolutionary curve simply represent non-detection of ^{6}Li, while those below the curve are interpreted as non-detections due to destruction of ^{6}Li in these stars. We will show in later discussion that this is compatible with their T_{eff}. It is straightforward to evaluate the survival fraction of ^{6}Li in the three stars through statistical bootstrapping, using the estimator:

$$\hat{g}_6 \equiv \frac{(^6Li/H)_{obs}}{(^6Li/H)_{pred}}. \tag{3}$$

In using this estimator, it is implicitly assumed that no production of ^{6}Li took place in the star, *i.e.* we neglect any flare production (Deliyannis & Malaney, 1995); we will return to this point in Sec.3. In this bootstrapping, we draw at random, according to their statistics, the 'observed' and the 'predicted' abundances. We draw the predicted protostellar abundances for the three stars from the same evolutionary curve, so as to ensure that the slope of the ^{6}Li correlation *vs* [Fe/H] is 1 in the halo phase. We do not correlate the systematics of the observed abundances, since these stars have different metallicities and different T_{eff}. We took care to include the metallicity statistics of the stars in the bootstrapping, taking into account the correlation of $(^6\mathrm{Li/H})_{pred}$ with metallicity. The resulting $\hat{g}_6$ histogram is shown in Fig.3 for a sample size of 10^6.

We thus obtain the following averages and 95% c.l. limits on g_6, in the standard case:

HD84937	$\overline{g}_6 = 1.92$	$0.57 \leq g_6 \leq 7.24$
HD201891	$\overline{g}_6 = 0.14$	$0.02 \leq g_6 \leq 0.54$
HD160617	$\overline{g}_6 = 0.38$	$0.00 \leq g_6 \leq 1.67.$

The lower limit on g_6 for HD160617 is 0.00: it could have been expected on the basis that ^{6}Li was not detected at the 2σ level in this star. We checked that the figures above were not sensitive to the type of statistics adopted for the systematics and the theoretical modeling, within $\simeq$10%.

With our present assumption that flare production of lithium did not occur in these stars, $\overline{g}_6 > 1$ is unphysical. One usual remedy is to use Bayesian statistical inference,

and to truncate the $\hat{g}_6$ probability with (for instance) a top hat function $\Theta\left(\hat{g}_6\right)\Theta\left(1-\hat{g}_6\right)$, to enforce $0 \leq \hat{g}_6 \leq 1$, and re-normalize the $\hat{g}_6$ distributions; in that case, the resulting 95% c.l. limits would become (0.26,0.99) for HD84937, (0.03,0.48) for HD201891, and (0.03,0.91) for HD160617, and the averages: 0.71 for HD84937, 0.14 for HD201891, 0.30 for HD160617. We note, however, that these numbers are subject to the (subjective) choice of constraints applied on $\hat{g}_6$, as is the case in any Bayesian inference procedure. The use of a top-hat uniform law is justified as a zero-th order choice when one does not have any more reliable guess to offer. This is the case here, since so-called 'standard' isochrones do not agree with each other as to the degree of destruction of ^{6}Li in these stars (see Chaboyer, 1994, on the one hand, and Deliyannis et al., 1990, on the other hand).

Another remedy is to invoke potential uncontrolled systematics, which, in the present case, should be associated with the estimates of the ^{6}Li/$^{6+7}$Li ratio. Indeed, as pointed out by Nissen (1995), convective motions in the stellar atmosphere result in an asymmetry of the profile, that might mimic ^{6}Li absorption in the LiI line. The choice of the type of absorption profile also plays an important role in the estimate of the ^{6}Li/$^{6+7}$Li ratio. Although these effects were taken into account by Nissen (1995), Nissen et al. (1995), using the nearby FeI and CaI lines as standards, the choice of these lines is dictated by convenience alone, and some mimicking of ^{6}Li is still possible. Such systematics could be ascertained using a greater sample of lines as standards; obviously, higher spectral resolution at high signal-to-noise ratio would allow a substantial increase in the accuracy of these estimates. A zero-th order estimate of such systematics is given by the difference of the observed to the predicted abundance of ^{6}Li in HD84937, yielding a reasonable offset of +0.3dex. This star is indeed the hottest of the three stars, and, for $T_{eff} \simeq 6300$, possibly no depletion of ^{6}Li is expected in stellar models (Brown & Schramm, 1988; Deliyannis et al., 1990, Chaboyer, 1994), depending on the (unknown) evolutionary status of HD84937, whose photometry puts it at the turn-off. Note that such systematics would not be in contradiction with the other two stars, that are main-sequence dwarfs with $T_{eff} \simeq 5800$, for which moderate to strong ^{6}Li depletion is expected. Thus, if we shift, by hand, the observed data point, to place it right on top of the predicted curve, the 95% c.l. limits on $\hat{g}_6$ in HD84937 become (0.30,3.16). It is comforting to note that both remedies used above, to enforce $\overline{g}_6 \leq 1$, lead to a very similar 95% c.l. lower limit on $\hat{g}_6$.

Finally, in order to check the consistency of the derived depletion factors with stellar isochrones for ^{6}Li survival, we plot in Fig.4 the observed data points and upper limits *vs* T_{eff}. Unlike ^{7}Li, however, for which the measured abundances are at the same level on the Spite plateau, the ^{6}Li data points need to be corrected for their trend with metallicity; in Fig.4, they were brought back to the metallicity of HD84937. It is obvious from Fig.4 that the locus of these data points is consistent with the expected shape of isochrones, as shown in Chaboyer (1994) for instance, and, more specifically, that none of the upper limits derived contradict the three detections. Moreover, we did not reproduce the isochrones of Chaboyer on Fig.4, since most of these stars are located near the turn-off, and the

isochrone seems to depend strongly on the evolutionary status of the star (Chaboyer, 1994). As well, note that to change the opacities used in the code is sufficient to modify the ^{6}Li depletion factor from 0 to $\simeq 3$ (in the subgiant case), which means, conversely, that we cannot rely too much on these models. In any case, the general agreement is very satisfying.

To conclude this section, we obtain a 95%c.l. lower limit on the survival fraction in HD84937, $g_6 \geq 0.26$ (equivalently $D_6 \leq 4$ for the depletion factor), assuming some uncontrolled systematics in assessing the line profile of the ^{6,7}Li λ6708Å line, or using Bayesian inference to bring back the measured average $\overline{g}_6$ in the physical region $\overline{g}_6 \leq 1$. It is well known that ^{6}Li is much more fragile to nuclear burning than ^{7}Li (*e.g.* Brown & Schramm, 1988, and references therein). As a consequence, the preservation region of ^{6}Li is, at any time, much shallower than that of ^{7}Li. As a consequence, ^{6}Li is also more sensitive than ^{7}Li to depletion mechanisms such as dilution processes, or even mass-loss (Vauclair & Charbonnel, 1995). Therefore, it seems reliable to use the lower limit on g_6 as an extreme lower limit on the ^{7}Li survival fraction g_7. Our evaluations thus show that at least one star on the Spite plateau has depleted its ^{7}Li by less than a factor 4, at 95% c.l.. Using the observed abundance of ^{7}Li in HD84937, Log(^{7}Li/H)$=-9.77 \pm 0.16 \pm 0.2$ (95% c.l. estimates for both statistical and systematics), we derive an upper limit on the primordial abundances of ^{7}Li, Log(^{7}Li/H)$_p \leq -8.81$ (95% c.l.), where we added linearly the errors and the upper limit on the depletion factor. Although this upper limit is not too stringent in itself, we note that, in order to saturate the upper bound, one would have to deplete <u>both</u> ^{6}Li <u>and</u> ^{7}Li by the same amount (a factor 4), and yet reproduce all the observed features of the Spite plateau, namely the uniformity in abundances and the isochrones. The above constraint is therefore stronger, *i.e.* it amounts to $D_7 \lesssim 2$, since there is, at our knowledge, no stellar model able to reproduce the observed trends, while having $D_7 \geq 2$ and $D_6 \leq 4$. We note, for instance, that, if the maximal depletion of ^{6}Li were due to pure nuclear burning without dilution, then ^{7}Li would be depleted by less than 2% from its primordial value (Brown & Schramm, 1988). As well, the rotational mixing models (Pinseonneault et al., 1992) satisfy the latter constraint on the features of the Spite plateau with a primordial abundance Log(^{7}Li/H)$_p \sim -9$, but cannot do without a depletion factor $D_6 \gtrsim 25$ (Deliyannis & Malaney, 1995).

3 Alternative scenarios

As mentioned earlier, the only way ^{6}Li can avoid a primary behavior for the whole range of metallicities $-4 \leq$[Fe/H]≤ 0, comes through the $\alpha - \alpha$ fusion channel. To discuss these 'non-standard' cases, we are compelled to restrain ourselves to specific models: arbitrary tuning of the cosmic ray flux, referred to as *(i)* in Sec.1.1, spallation in globular clusters (Tayler, 1995), or stellar flare production of ^{6}Li (Deliyannis & Malaney, 1995).

3.1 Early bright galactic phase

As discussed earlier, different models have been proposed to tune the cosmic ray flux so as to reproduce the observed abundances of ^{9}Be and B in the galactic halo. Ryan et al. (1992) suggested an outflow model with an enhanced supernova rate in the halo phase; since the injection flux is traditionally assumed to be proportional to the supernova rate, it was believed that it would allow the production of higher Be and B abundances. This is incorrect in that increasing the supernova rate leads to an increase in the production of metals, so that a higher ^{9}Be or B abundance would be associated with a higher metal abundance, and no difference with the standard model would be noted in an elemental graph Log(^{9}Be/H) *vs* [Fe/H]. The higher ^{9}Be and B abundances were rather obtained in an *ad-hoc* fashion by normalizing the yields to the observed ^{9}Be abundance at [Fe/H]=-1; in particular, a slope 2 is obtained. The role of the outflow was to evacuate the gas to prevent a high supernova rate in the disk phase, so as to prevent an overproduction of ^{9}Be and B at solar metallicities (see Fig.3 in Prantzos et al., 1993 for an illustration of these effects). Therefore, since further observations of Pop II ^{9}Be and B abundances seem to confirm a slope of 1 on the whole range of metallicities $-4 \leq$[Fe/H]≤ 0, we need not consider this model further. This remark also applies to the models of Prantzos et al. (1993), where the path length was tuned in the halo phase so as to reproduce the ^{9}Be and B abundances; although this model was nicely motivated, namely the cosmic rays should be overconfined in the halo phase, it led to a slope $\simeq 1.75$ for ^{9}Be and B, and, in any case, to a slope $\simeq 1.0$ for Li.

Finally, in Fields et al. (1993) it was shown that to reproduce a slope of 1 for ^{9}Be and B, the cosmic ray flux should vary approximately inversely with time. These authors did not offer an explanation for such a behavior: they were rather interested in constraining the duration and luminosity of an early bright galactic phase under the assumption that the cosmic ray flux would effectively vary as $1/t$. It was shown that the bulk of the γ-ray background could be associated with such an enhanced cosmic ray flux in the first few billion years. Nevertheless, according to the above discussion, Ryan et al. (1992) have shown that an increased supernova rate would not lead to a slope 1, and Prantzos et al. (1993) have shown that an overconfinement would not do so either. Hence, the only remaining explanation for a GCR flux varying as the inverse power of time would be to have the injection flux evolve as a high power of the supernova rate, which does not have a physical basis at the present time. Indeed, with (O/H)$\propto t^n$, $n \lesssim 1$, one would require $\phi_{inj} \propto (dN_{SN}/dt)^{1/1-n}$. Finally, we note that Lemoine et al. (1996) have shown that the GCR propagated flux should evolve as a very low power < 1 of the supernova rate, throughout the disk phase, in order not to overproduce the LiBeB abundances at solar metallicity. Thus, the higher power could only apply in the early pre–disk phase.

3.2 Spallation in globular clusters

Tayler (1995) has offered an original explanation to the primary behaviors of ^{9}Be and B in the halo phase, in suggesting that the bulk spallation would take place in globular cluster sized objects before the gas would be swept out of the cluster and mixed with the ISM gas. The primary behavior arises from the assumption that every globular cluster ejects the same amount of gas, and that the spallation is the same in every cluster: each time metals (Z) are ejected to enrich the ISM, LiBeB elements are also ejected, with a constant $(\mathrm{LiBeB/Z})_{ejec}$ ratio, that is independent of the Z content of the ISM. This ratio should not in fact be constant, as these globular clusters should not eject exactly the same amount of metals, and the spallation is not expected to be exactly the same in every object, so that, in the end, one would expect to observe a linear relation Log(^{9}Be/H) *vs* [Fe/H] with some scatter. There has indeed been a recent claim for a scatter around the linear trend (Primas, 1995), which gives credit to this scenario.

This model is nonetheless subject to relatively strong requirements. It assumes that all globular clusters eject nearly the same amount of metals, which, in a first approximation, would mean that they all have very similar masses. Moreover, it is assumed that the spallation is much more efficient in the globular clusters than in the ISM. Finally, the (^{9}Be/O) production ratio has to be arbitrarily tuned to that observed in the disk phase, since the linear behavior of ^{9}Be *vs* [O/H] is observed on the whole range $-3 \lesssim$[O/H]$\lesssim 0$ (Fig.2). On this basis, it is unfortunately difficult to say whether or not the (Li/O) production ratio is the same in these globular clusters and in the disk phase, since the (Li/Be) ratio depends very strongly on the spectral slope and the confinement time of the accelerated projectiles (Fields et al., 1993, 1995). Hence, no reliable evolutionary curve for ^{6}Li can be constructed in this case.

3.3 Flare production

Deliyannis & Malaney (1995) have studied the possibility of generating the observed ^{6}Li of HD84937 *via* flare production. They argue that the energetics can, in principle, be fulfilled. However, we disagree with their estimate of the energetics required, and we show below that such a model is strongly disfavored for producing all the observed ^{6}Li. These authors also propose two observational tests to possibly discriminate *in situ* flare produced ^{6}Li from proto-stellar ^{6}Li: *(i)* the ^{6}Li/^{9}Be and B/Be ratios in HD84937; and *(ii)* the curve of ^{7}Li/^{6}Li ratios the effective temperature in a sample of metal-deficient dwarfs. We disagree with these authors on the feasibility and the reliability of these tests, as we discuss now.

The first test of Deliyannis & Malaney (1995) to distinguish *in situ* flare produced ^{6}Li from proto-stellar ^{6}Li relies on the difference between the ^{6}Li/^{9}Be and B/Be ratios resulting from flare production and those resulting from cosmic ray spallation. However, it is straightforward to show that, even if all ^{6}Li observed in HD84937 were produced by

flares, the amount of Be and B produced by these flares would be negligible with respect to the amount of Be and B observed in this star. Using the flare production ratios of Walker et al. (1985), ^{6}Li/^{9}Be$\sim 40-100$ for a solar metallicity star, and rescaling it to a metallicity [Fe/H]=-2.1, this ratio should become ^{6}Li/^{9}Be$\sim 10^3 - 10^4$ in HD84937, since ^{6}Li is still produced through $\alpha-\alpha$ fusion, but the p–C,N,O channel is cut off. This ratio has to be compared with the observed ratio ^{6}Li/^{9}Be$\simeq 66^{+90}_{-45}$ (95% c.l.): clearly, if all observed ^{6}Li has been produced *in situ* by flares, then only a tiny (and negligible) fraction of the observed ^{9}Be comes from these flares. This conclusions holds true for B as well, and therefore, the ^{6}Li/Be and B/Be ratios cannot be used to trace *in situ* flare production.

The Deliyannis & Malaney second observational test rests on the dependence of the observed ^{7}Li/^{6}Li ratio with the effective temperature in subgiants. Deliyannis & Malaney (1995) have shown that this ratio should remain constant if the observed ^{6}Li is of proto-stellar origin, in the range of temperatures 6400$\geq T_{eff} \geq 5800$, as neither of both isotopes is then depleted. If ^{6}Li has been created in flares, the isotopic ratio should decrease with decreasing temperature, in the same range of temperatures, due to increased dilution (*i.e.* larger convection zone) past the turn-off. Indeed, the essential difference between proto-stellar and flare produced ^{6}Li is that the proto-stellar ^{6}Li preservation region is considerably larger than the convection zone post turn-off, whereas the only region containing flare produced ^{6}Li is the convection zone itself. This behavior is, however, very dependent on the evolution of the convection zone, which is difficult to model during the ascent on the subgiant branch. Moreover, as pointed out before, it seems that the survival of ^{6}Li in these stars depends strongly on the opacities adopted. Overall, it seems that, even if a large database of ^{7}Li/^{6}Li ratios in metal-poor stars could be collected, a possibility that is already very optimistic, this would not readily allow one to discriminate between flare produced and proto-stellar ^{6}Li.

We now turn to the energetics required for producing ^{6}Li in flares in HD84937. Deliyannis & Malaney (1995) argue that the production efficiency is 10^{-3}–1 atom/erg, so that 10 flares per year of strength 10^{32} ergs, which corresponds to the large solar proton flares, for 1 atom/erg, during 1Gyr, would reproduce the observed ^{6}Li. The point is that large proton flares, in the Sun, are associated with steep power law spectra (Ramaty et al., 1995), and the efficiency for these spectra is $\simeq 0.007$ atom/erg (with a low-energy cut-off imposed at 1 MeV) for a solar composition (R. Ramaty, 1996, private communication). We calculate that for a composition rescaled to the metallicity of HD84937, this estimate goes down to $\simeq 0.003$ atom/erg, assuming a 1 MeV cutoff. The Deliyannis & Malaney estimate of 1 atom/erg is therefore too optimistic by a factor $\simeq 300$, and instead of 10 flares per year, $\simeq 3000$ flares per year of a strength comparable to that of the large solar flares would be required, an enormous number indeed.

Here we investigate in greater detail the production of lithium in flares. We use only the $\alpha-\alpha$ fusion channel in our calculations, since with its threshold and peak resonances around $\simeq 10$ MeV/n, and the low metal content of the star, it should largely dominate

over the p,α–C,N,O channel. We assume an abundance $n_\alpha/n_p = 0.1$ in the accelerated and target particle abundances, although for large solar flares, the accelerated abundance could be lower by a factor 10 (Murphy et al., 1991). We also assume that, through downward convection, all the ^{6}Li produced in flares would be mixed in the convection zone of mass M_c. In a thick target model, the rate of ^{6}Li production can be written (Ramaty & Murphy, 1987):

$$Q\left(^6\mathrm{Li}\right) = \frac{1}{m_p}\frac{n_\alpha}{n_p}\int_0^{+\infty}\sigma_{\alpha\alpha}^{^6\mathrm{Li}}(E)\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\alpha^{-1}\int_E^{+\infty}N_\alpha(E')\,\mathrm{d}E'\mathrm{d}E, \tag{4}$$

where $Q\left(^6\mathrm{Li}\right)$ is in atom.s^{-1}, $(\mathrm{d}E/\mathrm{d}x)_\alpha$ represents the energy losses of α nuclei in the interaction medium, in MeV.g^{-1}.cm^2, and $N_\alpha(E)$ is the injection spectrum of α particles in (MeV/n)$^{-1}$.s^{-1}. This latter can be parametrized by a power law, a decreasing exponential in rigidity, or a Bessel function K_2 of the second kind, although we note that this latter reproduces more adequately the observational data on solar flares. It is also customary to define the deposited power:

$$\dot{W} = \sum_i A_i \int_0^{+\infty} E\,N_i(E)\,dE, \tag{5}$$

where A_i denotes the atomic mass of nucleide i. The production efficiency, referred to above, is then defined as $Q\left(^6\mathrm{Li}\right)/\dot{W}$, in atom.erg^{-1}. Here, however, we calculate the rate of production of ^{6}Li nuclei, using Eq.4, normalizing the injection spectrum to the observed rate of average irradiation of the solar atmosphere, *i.e.* $N_p\,(> 30\mathrm{MeV}) \simeq 3.10^{26}$ protons.s^{-1} (Ramaty & Simnett, 1991). We find that the production rate does not depend strongly (within a factor 2) on the type of spectrum chosen, or on the low-energy cut-off adopted for power law spectra. For power law spectra, we adopt a steep spectrum (index $\simeq 4$), with a low-energy cut-off of 1 MeV/n. Apart from preventing divergence, this cut-off is to simulate the presence of energy losses that flatten the spectrum at low energies. Due to the normalization adopted above, and the fact that the threshold of the $\alpha+\alpha \rightarrow {}^6$Li cross-section is ~ 10 MeV/n, our choice of cut-off maximizes the production rate. The production efficiency is strongly dependent on the type of spectrum, varying between $\sim 10^{-3}$ and $\sim 10^{-1}$ atom.erg^{-1}, in agreement with previous calculations (Canal et al., 1975, 1980). The production rate obtained is: $Q\left(^6\mathrm{Li}\right) \sim 2-4\times10^{22}$ atom.s^{-1}, which, after mixing in the convective zone, on a production timescale $\tau = 1$ Gyr, yields:

$$\left(\frac{^6\mathrm{Li}}{\mathrm{H}}\right) \sim 2-4\times10^{-15}\left(\frac{M_c}{10^{-3}M_\odot}\right)^{-1}\left(\frac{\tau}{1\mathrm{Gyr}}\right).$$

As compared to the observed ^{6}Li abundance in HD84937, (^{6}Li/H)$\simeq$ 9. $\times 10^{-12}$, this estimate is negligible. It has to be noted, however, that the mass M_c of the convection zone is largely unknown, mostly because the evolutionary status of HD84937 is itself unknown. Deliyannis & Malaney (1995) point out that M_c should range from $3\times10^{-4}M_\odot$

to $3 \times 10^{-3} M_\odot$, with an estimated $10^{-3} M_\odot$, if HD84937 is a dwarf, and from $7 \times 10^{-5} M_\odot$ to $1 \times 10^{-3} M_\odot$, with an estimated 3×10^{-4} if HD84937 is a subgiant. The mass of the convection zone also depends strongly on the stellar parameters, such as the mixing length, and, overall, the above estimates should be good within an order of magnitude. The estimate of a production timescale $\tau \approx 1$ Gyr stems from the dependence of the convection zone on age: since the convection deepens with age, on the main sequence, any spallated ^{6}Li is more likely to have been produced recently; Deliyannis & Malaney (1995) estimate 1 Gyr to be a reasonable timescale, and we adhere to this value. This shows that, even in the most favorable case (for flare production), *i.e.* a convection zone $M_c \sim 10^{-5} M_\odot$, the ^{6}Li abundance produced in flares remains more than an order of magnitude below the observed abundance. Recall as well that we assumed that the downward convection of flare produced ^{6}Li was fully efficient, that we assumed a "maximal" n_α/n_p abundance, and that we maximized the production rate in our choice of spectrum.

Hence, we feel that flare production of ^{6}Li cannot produce a significant contribution to the observed ^{6}Li abundance, unless HD84937 is subject to tremendously powerful flares over more than 1 Gyr.

4 Conclusion

We have estimated the depletion factor of ^{6}Li in the three metal-poor halo stars where it has been detected. In order to determine the proto-stellar ^{6}Li abundance in these stars, we have constructed an "empirical" evolutionary curve for ^{6}Li, deduced from the observed abundances of ^{9}Be. Namely, we have assumed that ^{6}Li/H scales as ^{16}O/H over the galactic lifetime, and normalized the resulting evolutionary curve to the meteoritic abundance of ^{6}Li. Our assumption is motivated by the recent observations of metal-poor stars, that revealed a slope $\simeq 1$ for the correlation of Log(^{9}Be/H) with Log(^{16}O/H). One may indeed recall that ^{6}Li and ^{9}Be share their origin in p,α–C,N,O spallation reactions (apart from an extra $\alpha - \alpha$ fusion channel for ^{6}Li).

We have taken care in assigning uncertainties to the so-modeled evolutionary curve of ^{6}Li. Notably, we have included new cross-section data for the primordial production of ^{6}Li. We form the ratio of the observed to the proto-stellar abundance to obtain the survival fraction g_6, *i.e.* the inverse depletion factor; the statistics of this survival fraction, in each star, are obtained from bootstrapping. We thus obtain a 95%c.l. limit $g_6 \geq 0.26$ (equivalently $D_6 \leq 4.$ for the depletion factor) in the hottest turn-off HD84937 ($T_{eff} \simeq$ 6300K). We have argued that some systematics, arising from the inaccuracy of stellar line profile modeling (at the precision required), should be associated with these measurements of the ^{6}Li/$^{6+7}$Li ratio, as there is always the possibility that some weak profile distorsion might mimic the ^{6}Li absorption. The above upper limit has been obtained in two different ways: assuming such systematics on the ^{6,7}Li line profile, and proceeding to Bayesian inference, to return the average $\overline{g}_6 \simeq 2.$ (measured for HD84937) into the physical region

$\overline{g}_6 \leq 1$.

Since ^{6}Li is much more fragile than ^{7}Li to nuclear burning, and since the preservation region of ^{6}Li is always shallower than that of ^{7}Li, this upper limit on the depletion factor D_6 is also an extreme upper limit on D_7, the depletion factor for ^{7}Li. At a minimum, this implies that at least one star on the Spite plateau, with abundance Log(^{7}Li/H)$=-9.77 \pm 0.16 \pm 0.2$ (95% c.l. for each error bars, statistical and systematics), has depleted its ^{7}Li by no more than a factor 4. This, in turn, means that an extreme upper bound can be put on the primordial abundance of ^{7}Li, Log(^{7}Li/H)$_p \leq -8.81$ (95% c.l.). We note that, in order to saturate this upper bound, ^{7}Li <u>and</u> ^{6}Li would have to have been depleted at the same level, by a factor 4. For instance, if depletion had occurred through direct nuclear burning, ^{7}Li would have to be depleted by no more than 2% for ^{6}Li to be depleted by a factor 4 (Brown & Schramm, 1988). As well, rotational mixing models (Pinseonneault et al., 1992), that claim to obtain a much higher depletion factor for ^{7}Li than 'standard' models, and yet reproduce all the observed features of the Spite plateau, are ruled out: in these models, a primordial abundance Log(^{7}Li/H)$_p \simeq -9$ is associated with a depletion factor $D_6 \sim 25-40$ (Deliyannis & Malaney, 1995). We know of no current stellar model able to reproduce the observed features of the Spite plateau, and yet allow $D_7 > 2$, while keeping $D_6 \leq 4$. The above constraint on the depletion factor of ^{7}Li on the Spite plateau is therefore stronger, *i.e.* ^{7}Li should not be depleted by more than a factor $\simeq 2$.

Finally, we showed that all three measured ^{6}Li abundances, as well as the upper limits derived, are in excellent agreement with all standard expectations: standard Big-Bang nucleosynthesis with $2 \leq \eta_{10} \leq 6.5$ (Copi et al., 1995, and references), 'standard' stellar models with respect to ^{7}Li and ^{6}Li survival in metal-poor stars, and standard early galactic evolution of both lithium isotopes (primary yields in spallation-fusion processes). The graph of ^{6}Li abundances *vs* T_{eff} obtained is also in good agreement with the expected shape for ^{6}Li isochrones.

It is obvious that future measurements of ^{6}Li abundances at different metallicities would narrow down the uncertainty in the possible depletion factors for ^{6}Li in these stars. It is equally obvious that such studies would greatly benefit stellar modeling physics and the determination of the primordial abundance of ^{7}Li. We recommend measurements of the ^{6}Li abundance at a metallicity [Fe/H]~ -1, since this the region where ^{6}Li detection is favored (see Fig.1). Moreover, such measurements, combined with those at lower metallicities, would allow the determination of the slope of the correlation Log(^{6}Li/H) *vs* [Fe/H], which we assumed to be $\simeq 1$.

We discussed three alternatives to the above scenario. Such alternatives can only arise from $\alpha - \alpha$ fusion creation of ^{6}Li, since this is the only channel whereby ^{6}Li and not ^{9}Be is produced. A condition on such alternatives is that they have to respect the primary behavior of ^{9}Be in the early Galaxy.

In the first case, we considered a logarithmic slope for Log(^{6}Li/H) *vs* [Fe/H], resulting from an arbitrary adjustment of the GCR flux to the inverse power of time. We argued that this scenario lacked any physical basis, since it would require the early GCR injection

flux to be tuned to a high power of the supernova rate, in order to reproduce the Be and B trends.

In the second case, where the bulk of LiBeB spallation would take place in globular cluster sized objects (Tayler, 1995), no firm prediction as to the behavior of ^{6}Li can be made at the halo-disk transition, hence no evolutionary curve can be constructed. This scenario remains as a possible loophole for obtaining higher depletion factors of ^{6}Li in HD84937. We note, in passing, that among the models proposed to account for the primary behavior of ^{9}Be in the halo phase, only this one and that of Cassé et al. (1995), Vangioni-Flam et al. (1995) seem credible at this time. In this latter, C,N, and O nuclei, freshly synthesized by supernovae exploding inside their parental molecular cloud, are accelerated and eventually decelerate or produce LiBeB nuclei through spallation on interstellar p and α.

Finally, we showed that stellar flare production of ^{6}Li cannot produce a significant contribution to the observed ^{6}Li, contrary to the suggestion put forward by Deliyannis & Malaney (1995).

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Table 1: Upper limits and measurements of the ^{6}Li/$^{6+7}$Li ratio in halo stars. Error bars are 95% c.l. estimates; when two error bars are quoted, the first corresponds to statistical errors, the second to systematics. References: *(a)* Ryan et al., 1996; *(b)* Thorburn, 1994; *(c)* Nissen, 1995; *(d)* Nissen et al., 1995; *(e)* Smith et al., 1993; *(f)* Hobbs & Thorburn, 1994; *(g)* Primas, 1995; *(h)* Spite et al., 1995. Evolutionary Status: T-o stands for Turn-off, Dw for Dwarf, and Sg for Sub-giant.

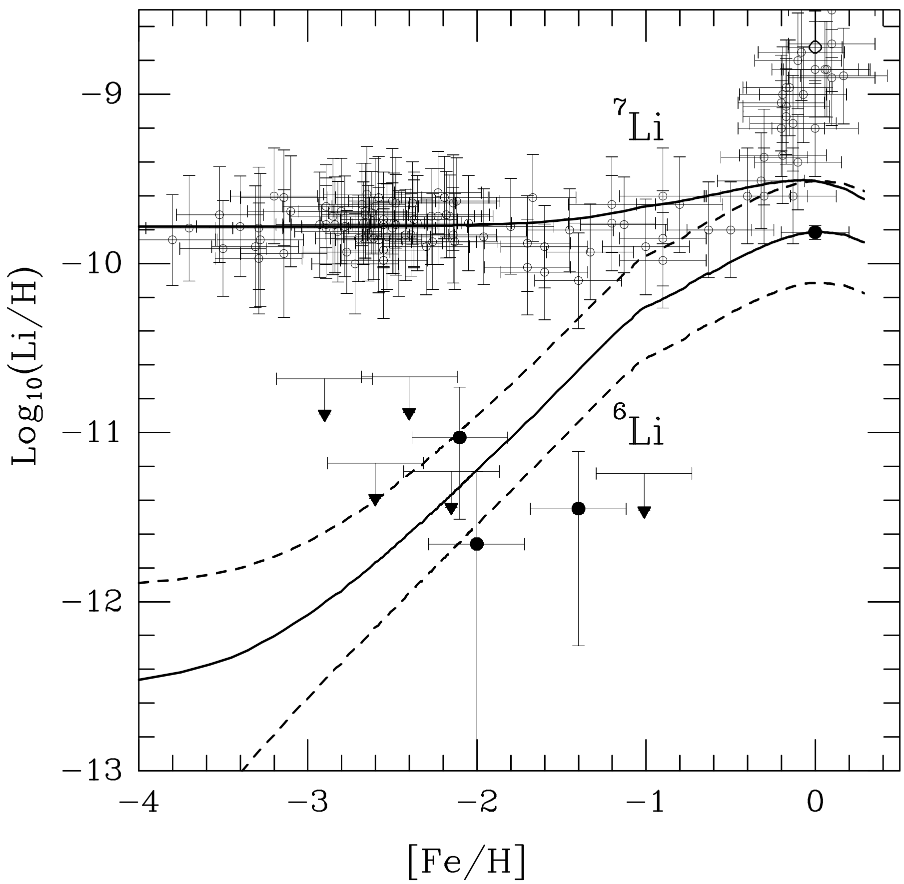
Star	T_{eff}	[Fe/H]	N[Li]	(^{6}Li/$^{6+7}$Li)	Status	Reference
HD84937	6280±150 ± 100	-2.1±0.16 ± 0.2	2.23±0.16 ± 0.2	0.055±0.034	T-o	*(a),(e),(f)*
HD201891	5800±150 ± 100	-1.4±0.16 ± 0.2	1.87±0.16 ± 0.2	0.048±0.040	Dw	*(a),(f)*
HD160617	5800±150 ± 100	-2.0±0.16 ± 0.2	2.11±0.16 ± 0.2	0.017±0.024	Sg	*(c),(g),(h)*
BD 3^{o}740	6340±150 ± 100	-2.9±0.16 ± 0.2	2.21±0.16 ± 0.2	$\leq$ 0.08	T-o	*(a),(f)*
BD 26^{o}3578	6150±150 ± 100	-2.4±0.16 ± 0.2	2.12±0.16 ± 0.2	$\leq$ 0.10	T-o	*(a),(f)*
HD19445	5850±150 ± 100	-2.1±0.16 ± 0.2	2.08±0.16 ± 0.2	$\leq$ 0.03	Dw	*(a),(f)*
HD76932	5770±150 ± 100	-1.0±0.16 ± 0.2	2.06±0.16 ± 0.2	$\leq$ 0.03	Sg	*(d),(g)*
HD140283	5660±150 ± 100	-2.6±0.16 ± 0.2	2.13±0.16 ± 0.2	$\leq$ 0.03	Sg	*(b),(g),(h)*

Figure 1: Graph of ^{7}Li and ^{6}Li abundances in halo stars; triangles denote upper limits, filled circles correspond to actual detections of ^{6}Li, and open circles to ^{7}Li abundances. Error bars are 95% c.l., obtained by summing quadratically statistical and systematics error bars. Solid curves represent the standard evolutionary curve for ^{6}Li and ^{7}Li (no stellar component is included for ^{7}Li), and the dashed curves delimit the 95% c.l. on the ^{6}Li prediction.

Figure 2: Graph of ^{9}Be abundances *vs* metallicity. The solid and dashed lines correspond to the ^{6}Li evolutionary curve and its 95% c.l. limits (without any primordial component) shifted to the level of ^{9}Be abundances.

Figure 3: Histogram of the statistics of the ^{6}Li survival fractions (g_6) in HD84937 (heavy solid), HD160617 (light solid), and HD201891 (dashed).

Figure 4: Plot of ^{6}Li abundances *vs* T_{eff}, after having corrected the observed abundances for their trend in metallicity, a slope 1 in our case, to the metallicity of HD84937, [Fe/H]$=-2.1$. The error bars on the abundances implied by this correction were not applied; other error bars are 95% c.l..



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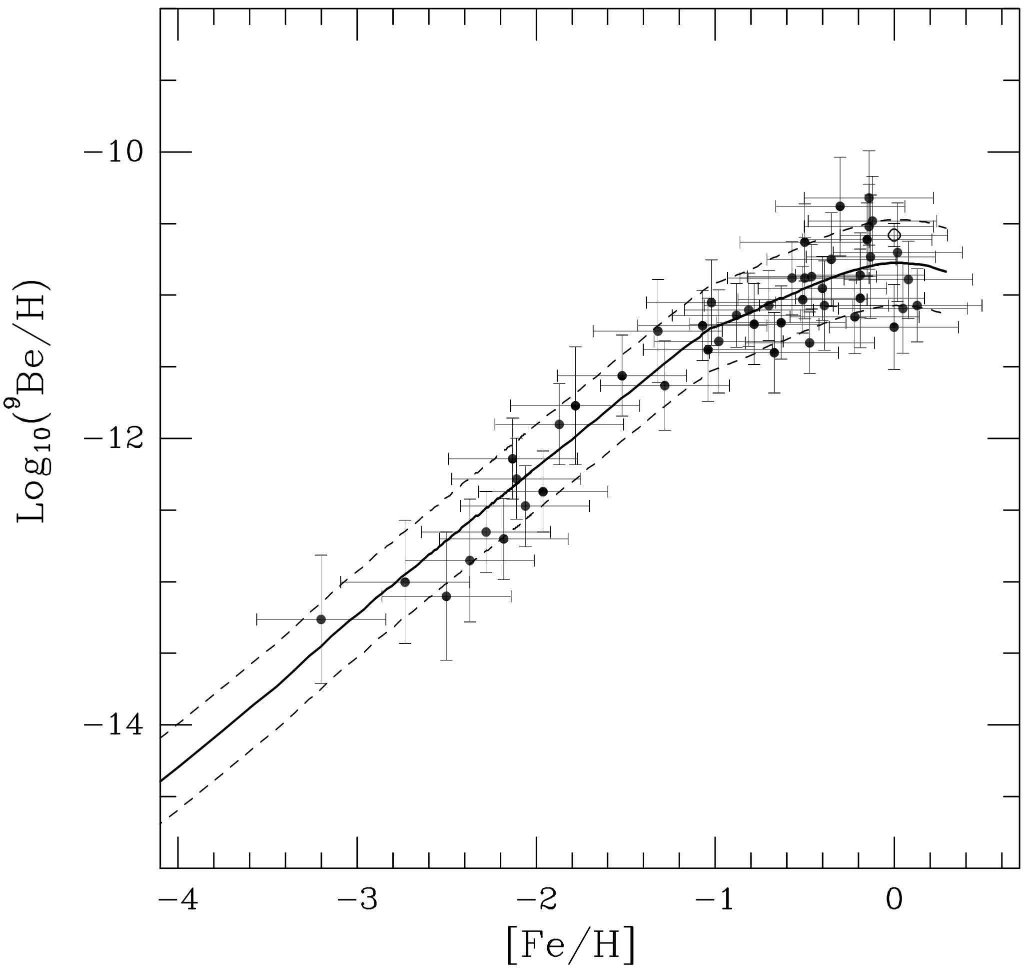

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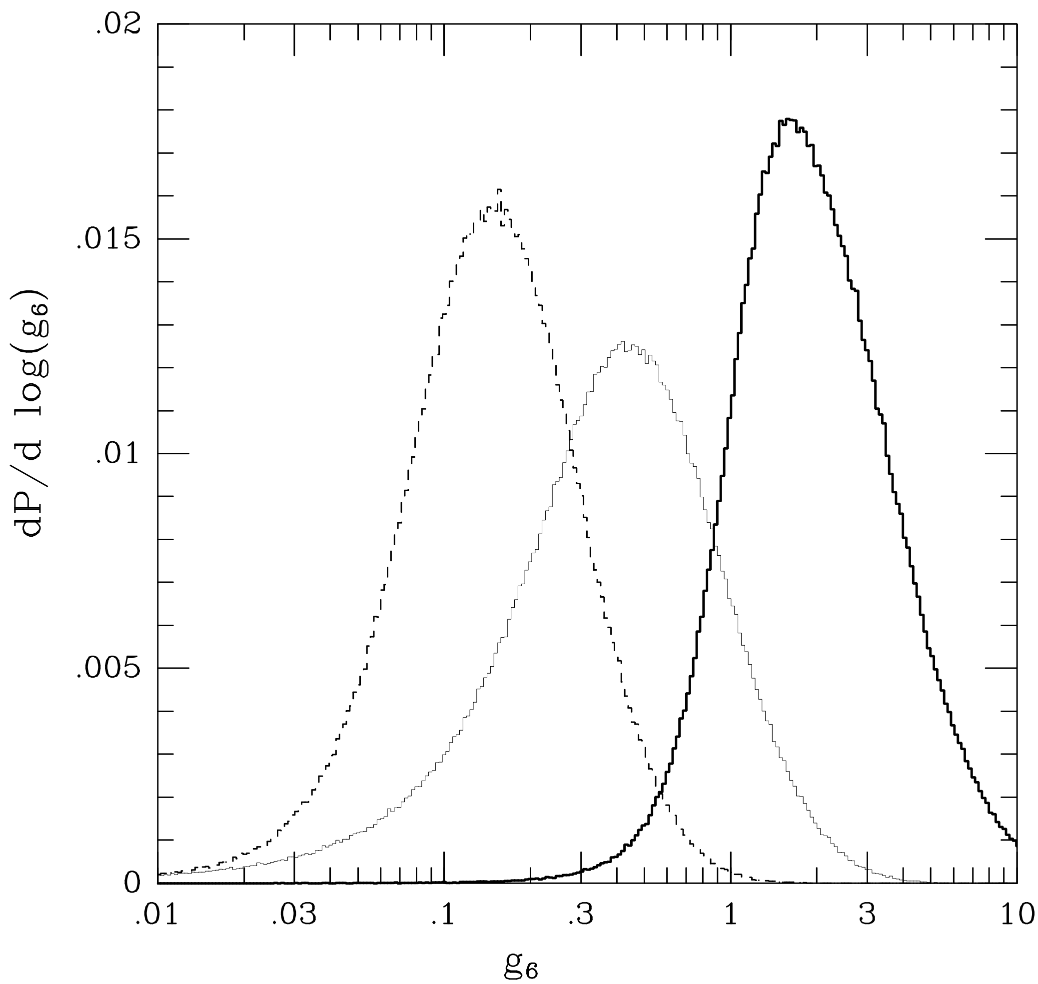

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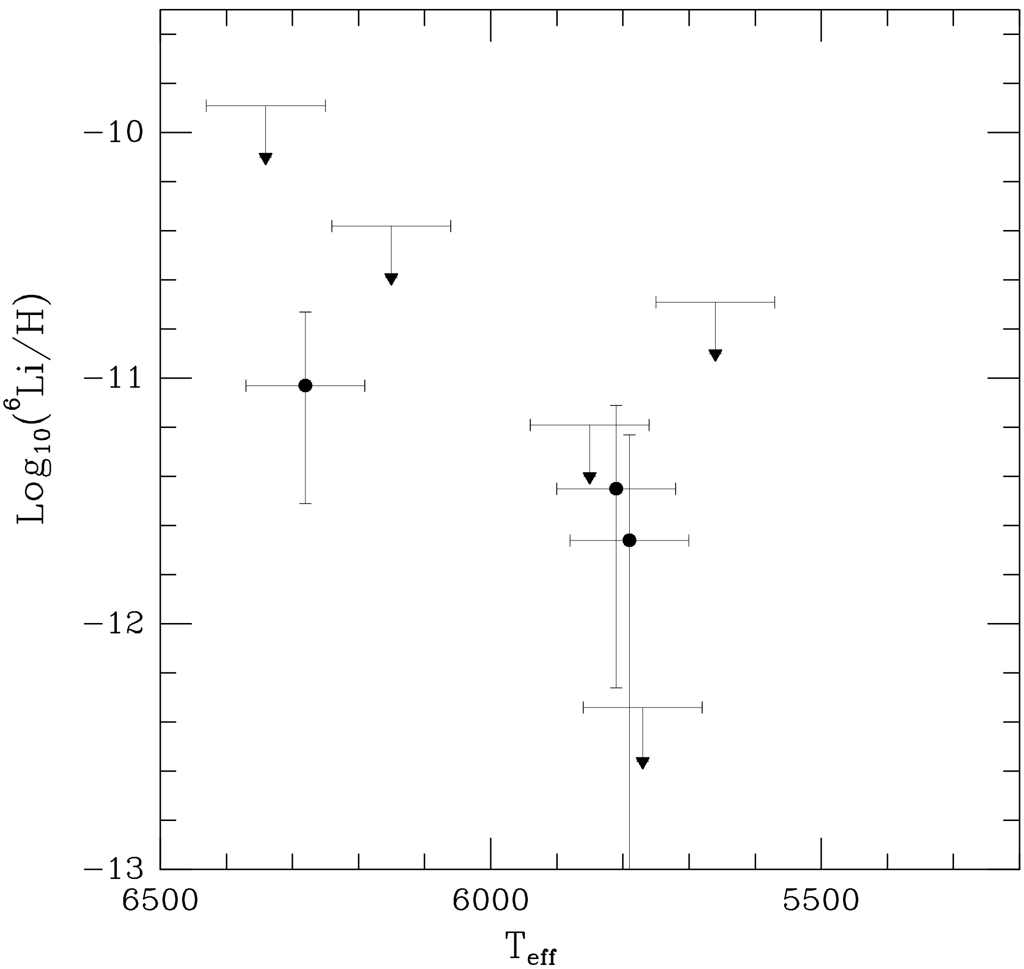

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